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COUPLING ATMOSPHERE AND WAVES FOR COASTAL WIND TURBINE DESIGN

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Offshore wind farms in coastal areas are considered by the Danish government to contribute to the goal of having 50% of the energy consumption from renewable sources by 2025. Therefore, new coastal developments will take place in Danish areas. The impact of waves on atmosphere is most often described by roughness length, which is typically determined by the Charnock formulation. This simplification in many atmospheric models has been shown to bring bias in the estimation of the extreme wind. Some wave-dependent formulations have been reported to overestimate the drag coefficient and roughness, but new roughness formulations have been proposed to better estimate wave-wind interactions according to observations. In the present work, an assessment of several roughness descriptions is performed, and implications for coastal wind and wave modelling are studied. An atmospheric (WRF) and spectral wave model (MIKE 21 SW) are implemented for the North Sea in order to consider wave effects on roughness. The objective is to see the reaction of an atmospheric model to the water surface description through offline coupling. A comparison with three simplified roughness formulations embedded in WRF showed a 50% variation in roughness and 20% in wind, with the better formulation for wind leading degraded predictions of roughness compared with observations. The large estimates of roughness when using a 3rd generation wave model are evident offshore, while a roughness formulation based on wave age produces more realistic values. However, at a coastal site, both estimates were within the same range. The impact of roughness on the wave model is discussed in terms of an idealized case for fetch-limited wave growth.

Keywords: wind modelling; wave modelling; wind-wave coupling; sea surface roughness; Charnock parameter

INTRODUCTION

Offshore wind farms in coastal areas are considered by the Danish government to contribute significantly to the goal of having 50% of the energy consumption from renewable sources by 2025. Therefore, new offshore wind farms with an overall capacity of 450 MW by 2020 shall be installed in the coastal areas. New challenges will arise, especially during storm conditions that directly may affect the estimation of wind turbine design parameters (like extreme metocean conditions, turbulence intensity and shear), the secure operation of the national and international electrical system (regarding e.g. the turbine cut-off speed), the fatigue and the extreme wave loads.

In current atmospheric modelling systems, the impact of waves is most often described by roughness length (z_0) which is determined by the Charnock formulation: $z_0 = \alpha u_*^2 / g$, where α is the Charnock parameter, u_* is the wind friction velocity and g is the gravitational acceleration. Many atmospheric models use a constant value for α ; the mesoscale model often employed for wind prediction, the Weather Research and Forecast (WRF) model, uses a constant of $\alpha=0.018$ per default. This oversimplified approach was shown to contribute to the underestimation of storm winds at hub height by up to 30% according to the measurements from the Horns Rev met-mast, and underestimates the 50-year wind by 11% (Larsén et al., 2013). It was also found to result in large bias in climate model prediction (Janssen and Viterbo, 1996).

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Sea surface roughness background

Since 1955, when Charnock proposed a roughness and wind friction velocity relation, there have been numerous works on trying to describe the sea surface roughness. Typical roughness values are of less than 0.01m for the sea. The dependence on wave properties was recognized early (eg. Kitaigorodskii and Volkov, 1965); parameters such as wave age, wave steepness, wave height, and spectral width, among others, have been used. The development of spectral wave models has also led to estimates of wind drag and sea surface roughness based on energy balance equation source functions, for example the Janssen (1991) spectral wave formulation (which is the “standard” in models like WAM 4.5 and MIKE 21 SW) considers the interaction of waves and wind to estimate a wind friction velocity (u_*) and roughness length (z_0) dependent on the input source function. However, it has been argued that, although this formulation produces good wave predictions for general operational applications, it overestimates the drag coefficient when compared with observations (Jensen et al., 2006; Powell et al., 2003). Similar overestimations were found (Chao et al., 2005) with the WAVEWATCH III formulation. The relatively small amount of simultaneous wind and wave measurements available and the large scatter of the data make the formulations inconclusive, and outline the complexity of the atmospheric surface layer over the ocean. Therefore, new wave-dependent roughness formulations have been proposed to better estimate wave-wind interactions according to observations. Fan et al. (2012) simulated 29 years of waves using a coupled HiRAM- WAVEWATCH III model and a z_0 based on field observations dependent on wind speed and wave age (c_p/u^* , c_p being the phase speed of the predominate waves). Similarly, Liu et al. (2011) coupled WRF-SWAN-POM for tropical cyclones taking into account wave-related effects like wave state and impact of sea surface current on wind stress. Chen et al. (2013) calculated the surface stress tensor using 2D wave spectra from WAVEWATCH III with added shortwave spectral tail. The wind and waves were coupled in a vector (stress) form, rather than through the scalar roughness.

The objective of the present work is to assess and validate several roughness formulations at a coastal location in Denmark and their implication for coastal wind and wave modelling. This area is subject of large wind energy developments that require accurate wind and wave information of both mild and extreme conditions.

THE WRF-MIKE 21 SW SYSTEM

The used models are the atmospheric model WRF and the third generation spectral wind-wave model MIKE 21 SW. WRF is a non-hydrostatic, fully compressible mesoscale model of atmospheric dynamics (Skamarock et al., 2005). It can be used with multiple nestings and two-way interactive grids. The version of WRF used in the present study is the 3.5 which contains several roughness length formulations.

MIKE 21 SW (Sørensen et al., 2004) is a third generation spectral wave model developed for flexible meshes and allows a high resolution near complicated coastlines. The model includes the Janssen (1991) formulation with the white-capping from Bidlot (2005). Figure 1 shows the MIKE 21 SW model domain and a snapshot of significant wave height (H_{m0}) field distribution corresponding to the 14/12/2003 – case study.

To understand the improvement through the wave information to the atmospheric modeling, it will be presented how WRF reacts to z_0 derived from wave modeling, in comparison to some of the simplified z_0 parameterizations (dependent on winds only) embedded in WRF. The evaluation considers site measurements from sonic anemometers as described in next section.

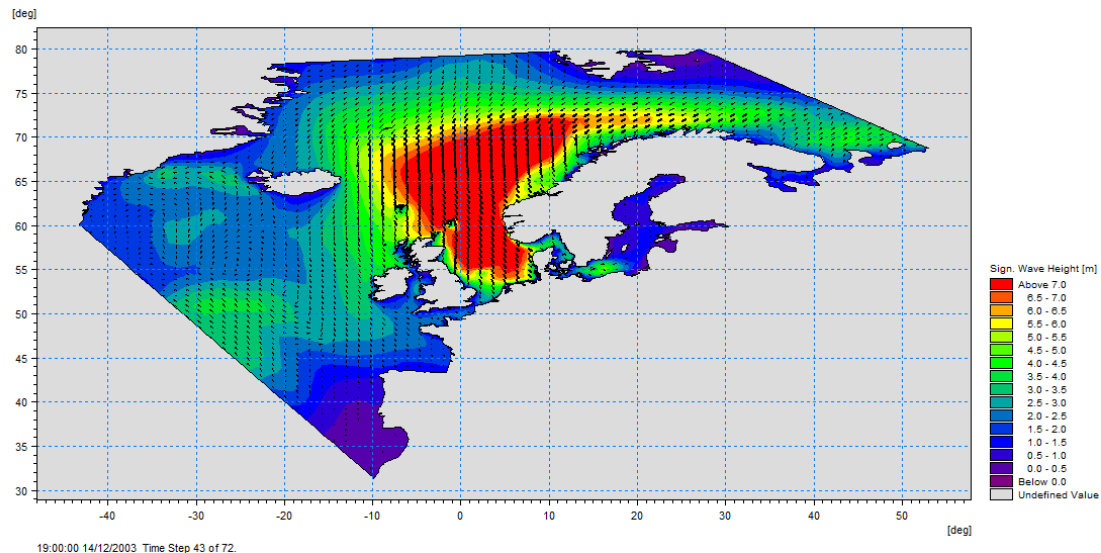


Figure 1. MIKE 21 SW model domain showing a snapshot of H_{m0} during the 14/12/2003. Vectors have been interpolated into a regular grid.

MEASUREMENTS

Measurements from Mast-2 from Horns Rev 1 (7.875° E, 55.508° N) were analyzed. Horns Rev is a coastal site (Figure 2) over relatively shallow water. The water depth at this area varies from 6 to 12m. It faces an open sea to the west. The shortest distance to shore is a bit more than 6km from 70° direction, but increases to about 27km in 120° direction. The mast data include 10-min standard meteorological measurements and high-frequency sonic data. Most data from Mast-2 were obtained before a wind farm was built and therefore free of the wake effect from the wind farm. Cup measurements of the wind speed are available at 15m, 30m, 45m and 62m (the mast top). The turbulence measurements of momentum and sensible heat fluxes are from one single level of 50m. At the same time, wave measurements were made through a Wave Rider buoy close to the mast (Saint-Drenan, 2009).

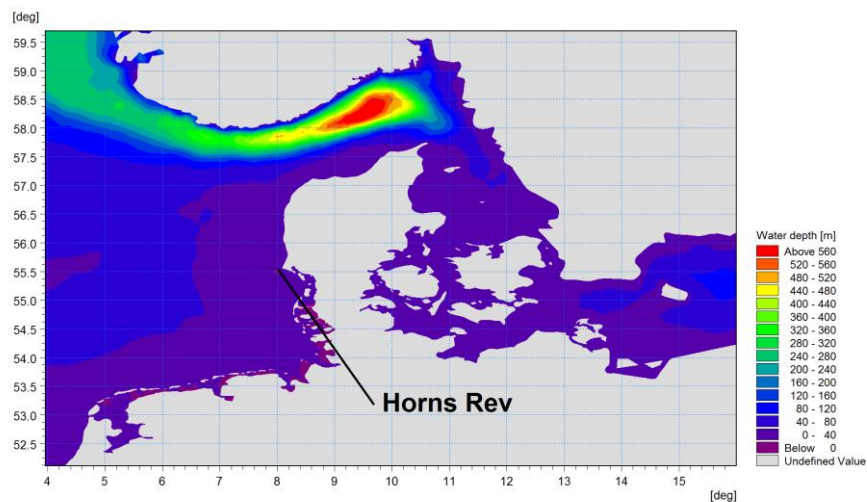


Figure 2. Location of Horns Rev sonic anemometers.

Figure 3 shows time series of wind and wave parameters during 3 days in December 2003 (13 – 15th). Wind speed at 15m above the surface reached 20m/s with a constant direction from the NW. Significant wave height reached 3m during the 14 of December. The roughness length has been estimated using the Charnock approximation. However, analysis of measurements during storm conditions showed that the 50m height is in the Monin-Obukhov surface layer, where the vertical wind distribution strictly follows a logarithmic wind law with stratification effect up to the mast top. This might suggests the use of turbulence measurements at 50m as an approximation of the surface fluxes and estimate the roughness length accordingly. This scatter in the data is commented in the discussion section and it is subject of current research.

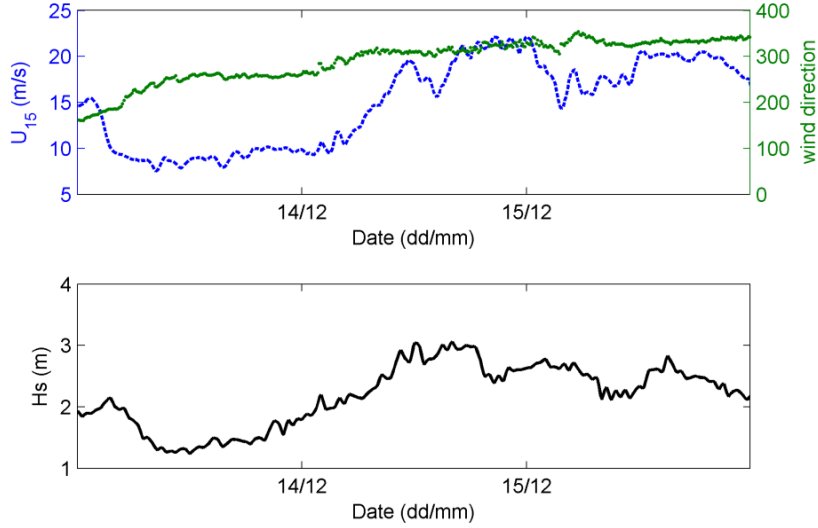


Figure 3. Time series of wind speed and direction (top panel) and significant wave height (bottom panel).

WRF SEA SURFACE PARAMETERIZATIONS

WRF version 3.5 includes several formulations for the estimate of sea surface roughness (z_0); we have used three of them to assess sensitivity and impact on estimates of wind speed.

Charnock formulation

The Charnock formulation is described as

$$z_0 = \frac{\alpha u_*^2}{g} \quad (1)$$

Where $\alpha = 0.018$

Davis et al. (2008) formulation

WRF uses a modified formulation based in Davis et al. (2008) and reads as:

$$z_0 = \left(1 - \left(\frac{u_*}{1.06} \right)^{0.3} \right) \left(\frac{0.011 u_*^2}{g} + 1.59 \cdot 10^{-5} \right) + \left(\frac{u_*}{1.06} \right)^{0.3} \left(10 \exp(-9.5 u_*^{-1/3}) + \frac{0.11 \cdot 1.5 \cdot 10^{-5}}{u_*} \right) \quad (2)$$

An upper and a lower limit on z_0 are used, namely 2.85×10^{-3} m and 0.125×10^{-6} m.

Taylor and Yelland (2001) formulation

Taylor and Yelland (2001) proposed a wave steepness dependent roughness described by:

$$z_0 = 1200h_s \left(\frac{h_s}{L_p} \right)^{4.5} \quad (3)$$

However, within WRF the estimate of significant wave height (h_s) is calculated using a fully developed seas assumption and wave parameters are defined as:

$$h_s = 0.0248u_{10}^2 \quad (4)$$

$$L_p = \frac{gT_p^2}{2\pi} \quad (5)$$

$$T_p = 0.729u_{10} \quad (6)$$

An upper and a lower limit on z_0 are used as in the Davis et al (2008) formulation.

Figure 4 shows the results of the z_0 estimates by WRF and measurements at the Horns Rev location. Significant variations are observed by the different formulations, being the Davis et al. (2008) the one giving the lowest values. A peak in z_0 is observed during the 14th in both models and data; however, the model predicts it a few hours earlier, Taylor and Yelland (2001) formulation gives closest values when compared to measurements during the 14th.

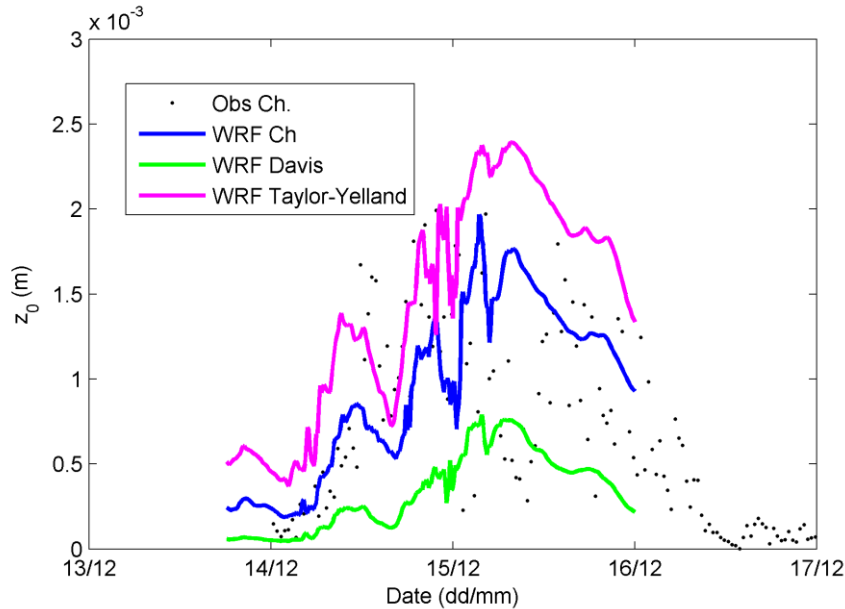


Figure 4. Time series of observed and modelled sea surface roughness (z_0) for WRF only formulations.

Figure 5 shows the model results in terms of wind speed (u_{15}); the reduced z_0 in the Davis formulation produces the highest wind speed which matches the first peak of the storm but produces a significant overestimation after the 15th when the Charnock formulation seems to do a better job although scatter is large.

The WRF sensitivity to z_0 formulations suggests that a more physical description of the roughness would be more appropriate. In the next sections, exploration of a wave-dependent roughness is

performed with the ultimate goal of improving wind, waves and its coupling modeling in fetch-restricted waters.

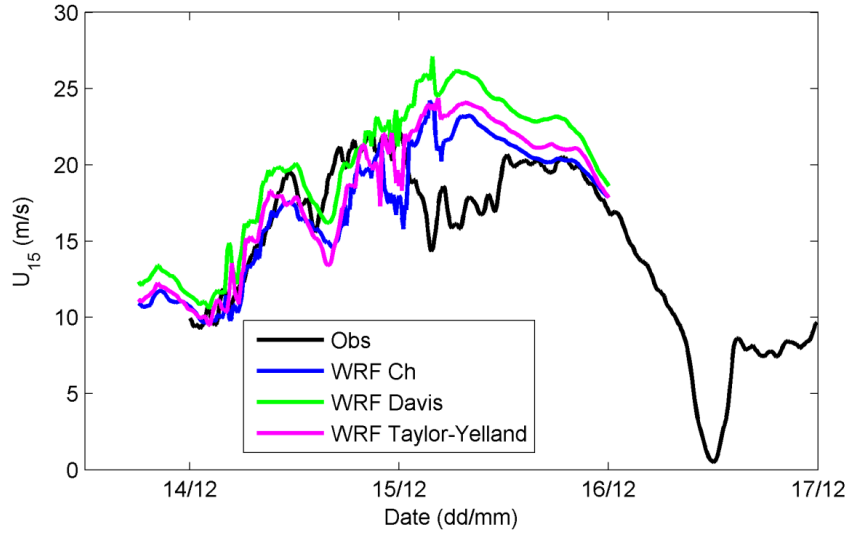


Figure 5. Time series of observed and modelled wind speed (u_{15}) for WRF only formulations.

WAVE-DEPENDENT SEA SURFACE PARAMETERIZATIONS

Additionally to the wind-dependent formulations for the estimate of z_0 , two wave-dependent formulations are used as described below. By considering wave properties in the estimation of z_0 , more scatter (physically based) than the wind-based is included.

Janssen (1991)

Within the Janssen (1991) theory, the Charnock parameter is dependent on the wave-induced stress, which at the same time is dependent on the wind input source term in a spectral wave model formulation. The Charnock parameter is defined as:

$$Zch = \frac{gz_0}{u_*^2} = \frac{\alpha}{\sqrt{1 - \frac{\tau_w}{\tau}}} \quad \text{where } \alpha=0.01 \quad (7)$$

τ is the total stress and τ_w is the wave stress which is estimated from the wind input source function as

$$\tau_w = \int d\omega d\theta \frac{k}{\omega} S_{in} \quad (8)$$

Where k is the wave number, ω is the angular frequency and S_{in} is the wind input source function in energy balance by Janssen (1991, 2004). The implementation in MIKE 21 SW is described in the model scientific documentation (MIKE by DHI, 2012).

Fan et al. (2012)

Fan et al. (2012) simulated 29 years of waves using a coupled HIRAM-WWIII model. In the coupled system, the roughness length is feedback to the atmospheric model as lower boundary condition. They reported that the original WWIII formulation gave values of z_0 of more than 0.012m (too high when compared with some observations), while a new formulation was of around 0.003m. The new z_0 formulation is a Charnock type which depends on wind speed and wave age (c_p/u^*) as described by

$$Charnock = \frac{z_0 g}{u_*^2} = a \left(\frac{c_p}{u_*} \right)^b \quad (9)$$

where a and b are fitting constant determined from nine different 10-meter wind speeds ranging from 10 to 50m/s:

$$a = \frac{0.023}{1.0568^{u_{10}}} \quad (10)$$

$$b = 0.012u_{10} \quad (11)$$

The above equations are solved together, along with

$$u_z = \frac{u_*}{k} \ln \left(\frac{z}{z_0} \right) \quad (12)$$

Figure 6 shows the spatial distribution of the two estimates of sea roughness, one using Janssen (1991) formulation and a second one by Fan et al. (2012), the fields correspond to the 13/12/2003. The large estimates of z_0 with Janssen (1991) are evident and are significant for Danish coastal waters. This is in agreement with the reported by Jensen et al (2006) during hurricanes. Fan et al. (2012) formulation produces smaller values in coastal and offshore areas. The correct estimate of z_0 is critical for a fully consistent wind and wave coupling, and there is not yet a well-established and fully accepted methodology; additionally, the large scatter in the few measurements complicates the parameterizations.

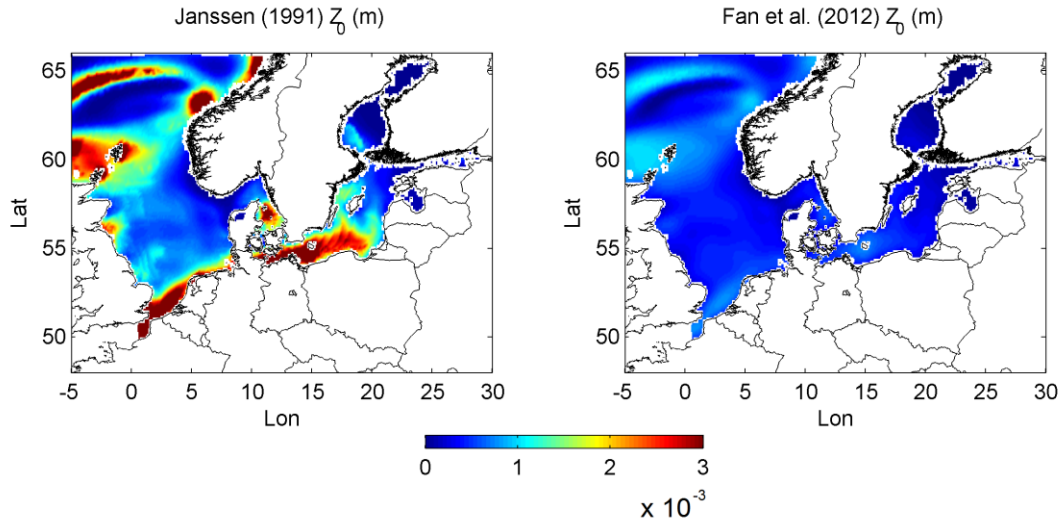


Figure 6. Distribution of z_0 when using Janssen (left) and Fan (right).

Figure 7 shows the time series of z_0 at the Horns Rev location for observations and both wave-dependent formulations. It is evident that the Janssen formulation gives larger values: the large values during the first hours of the simulation are due to the very young waves during the spin up of the model. Fan formulation is close to the WRF Charnock during the peak of the storm (the 14th). Janssen formulation seems to accurately predict the main peak of the storm when compared with observations at this station.

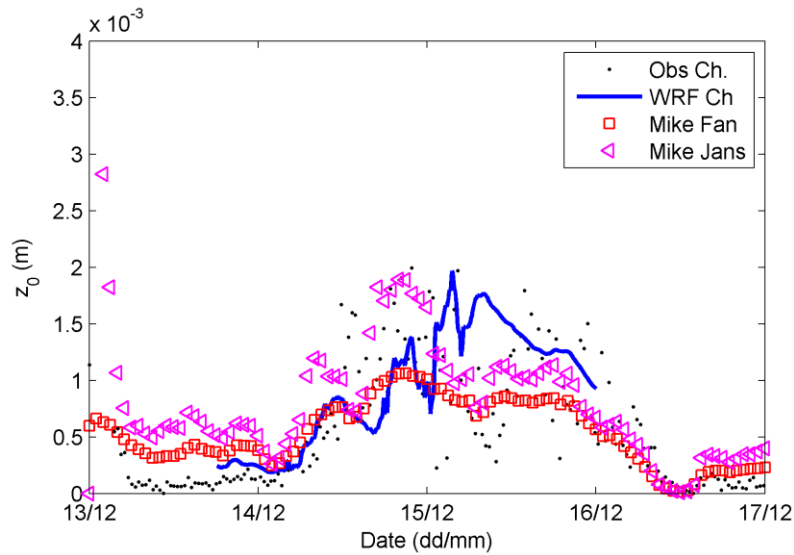


Figure 7. Time series of z_0 when using wave-dependent formulations.

Figure 8 shows the time series of u_{15} at the measurement location. The largest values of z_0 with Janssen formulation produce a small reduction of wind speed during the growth of the storm while when using Fan formulation wind follows the case using Charnock more closely. In a coupled system, all the variables should be consistent, and the first step towards it is through a direct validation with measurements instead of using proxies to other variables (eg, a good wind speed result does not imply a good roughness estimate).

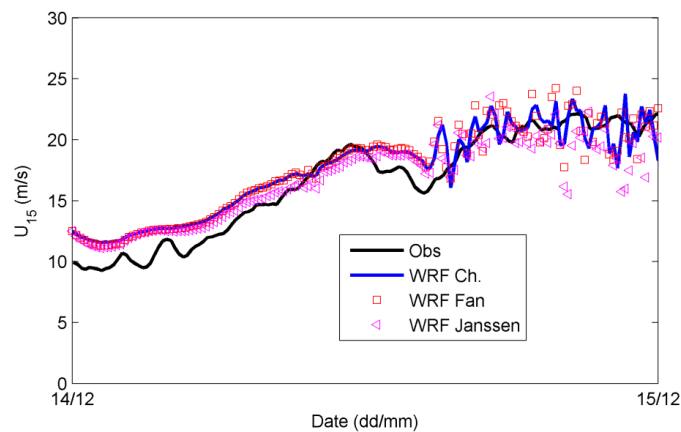


Figure 8. Time series of u_{15} when using wave-dependent formulations.

Effect of z_0 formulation on an idealized (fetch-limited) case

In order to see the effect of the different z_0 formulations (Charnock; Janssen 1991; and Fan et al. 2012) on wave generation, an idealized square domain of 40 x 40km and 500m depth was forced with constant (in space and time) winds of 15 and 30m/s. Growth curves proposed by Kahma and Calkoen (1992) for stable and unstable atmospheric conditions are used for comparisons.

Figure 9 shows the result of the fetch-limited case. For moderate wind (15m/s), results show lower scatter, Janssen (1991) giving the highest H_{m0} at all fetches. Fan et al. (2012) and Charnock formulation give very similar results. When comparing the results to curves obtained by Kahma and Calkoen (1992), it can be seen that all results fall within the range of the curves, Janssen approximating to the unstable (faster growth) curve and Fan and Charnock to the stable. However, for the more intense wind (30m/s), Janssen formulation gives significantly larger values of H_{m0} , and the wave growth curve falls

above the Kahma and Calkoen (1992). Charnock and Fan formulation give similar results, falling very close to the curve for stable conditions.

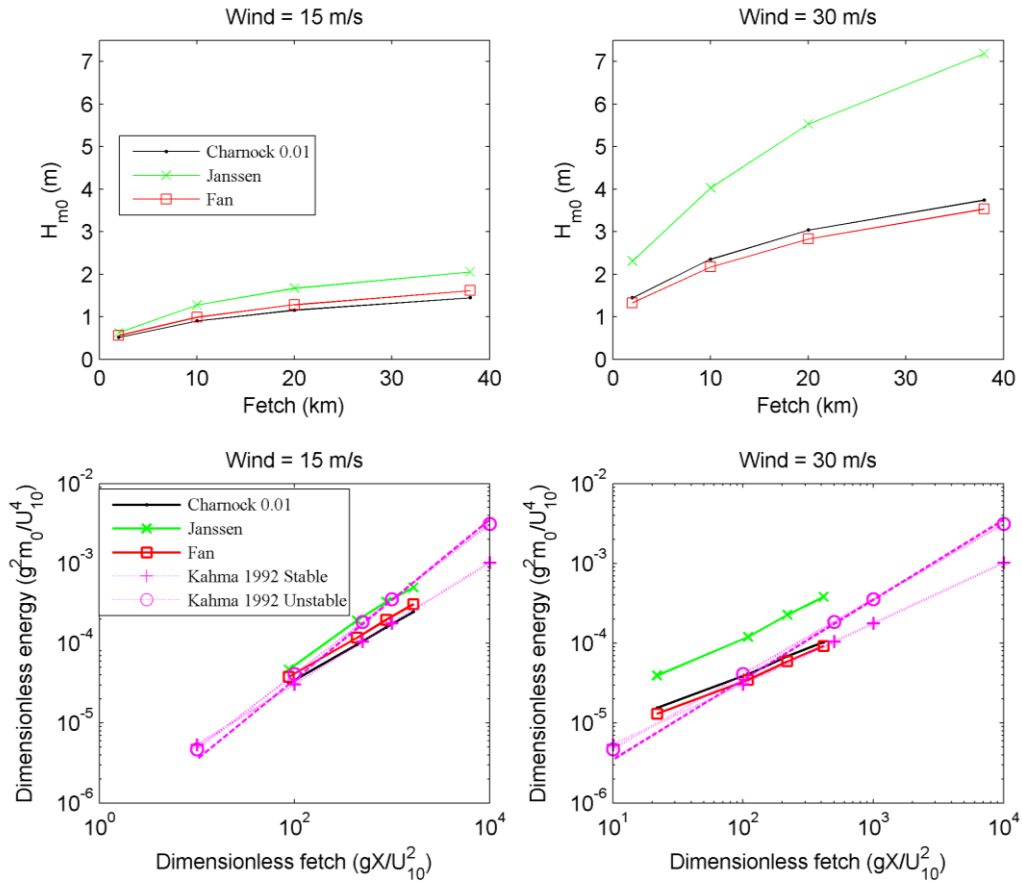


Figure 9. Fetch-limited wave growth for wind (u_{10}) of 15m/s (top-left panel), and 30m/s (top-right panel). Bottom row shows the results in idealized fetch and energy and compared with growth curves obtained by Kahma and Calkoen (1992). The dimensionless parameters use the wind speed (u_{10}), and gravity (g). X is the fetch and $m0$ is the total energy content in the wave spectra (zero-spectral moment).

DISCUSSION

In the previous sections, the results of sensitivity runs were presented together with some comparison with measurement data and idealized cases. It was shown significant variations in terms of z_0 and somewhat smaller in u_{15} . The Taylor and Yelland (2001) formulation implemented in WRF uses fully-developed seas which are not expected to be found in the North Sea during intense storm evolution, and thus values of H_{m0} and T_p might be overestimated. The inclusion of waves by using a spectral wave model provides a more realistic description of the sea state; however, the description of roughness should be validated directly with measurements of stress. In the present work, estimates of z_0 were done using the Charnock approximation ($z_0 = 0.018u_*^2/g$), but a preliminary analysis of measurements using the Monin-Obukhov similarity theory (MOST) seem to produce a larger range of z_0 values. This scatter in measurements is critical for a proper validation of z_0 estimates, which in a 2-way coupling of wind and wave models becomes one of the linked variables between the models.

A common approach to relate wave parameters to the roughness is via the wave age (eg. Fan et al. (2012) formulation); however, the self-correlation of z_0 and wave age (u^*/C_p) due to the friction velocity may be misleading. This is particularly true for shallow locations where wave celerity (C_p) is controlled by water depth and where energy and shape of waves can change drastically. Figure 10 shows scatter plots of the measured data at Horns Rev 1. The first panel shows the high correlation of z_0 with wave age, while the central panel shows the scatter of z_0 with C_p . It shows some pattern, for slower (small) waves z_0 is high as it is the small waves which support most of drag. For faster waves, the roughness shows more scatter. The third panel shows the scatter of z_0 with H_{m0} ; it shows a linear trend

with a correlation of $r=0.82$. This might indicate that at intermediate and shallow water depths, where celerity is uncoupled from wind due to bathymetric effects, other parameters rather than wave age may be a better parameterization of roughness. Under such conditions, wave height might be a better description of sea state and the roughness elements that waves represent on the wind field.

The roughness is not only dependent on wind speed and waves, there are other parameters such as atmospheric stability and sea spray that should be taken into account, and thus an estimate of roughness should be performed in a fully-coupled atmospheric and wave model in order to consider all these variables at the same time. The run of Janssen formulation in an offline (uncoupled) mode might have some inconsistencies as there is no feedback from waves to the atmospheric model.

The use of wave growth curves such as the ones proposed by Kahma and Calkoen (1992) derived from observations are a good reference for model validation and calibration when, for example, changing coefficients and constant in source terms. However, such curves were obtained from data under relative mild conditions and their use for more extreme ($> 25\text{m/s}$ winds) is questionable, and thus model comparison at this range of conditions should be taken with caution.

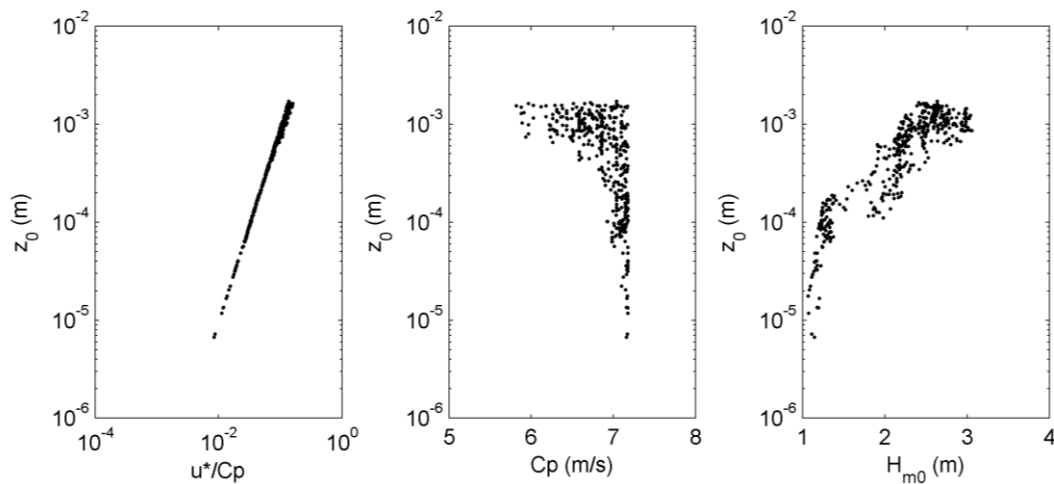


Figure 10. Scatter plot of measured data at Horns Rev. Left panel: roughness and wave age scatter plot. Center panel: roughness and wave celerity scatter plot. Right panel: roughness and significant wave height scatter plot.

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